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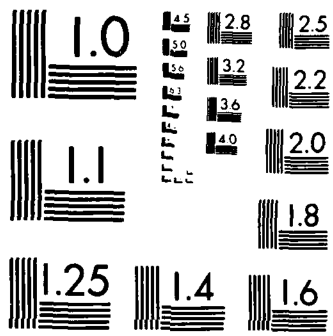

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TURBULENT REACTING FLOWS AND SUPERSONIC COMBUSTION

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Submitted by

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1.0 SUMMARY

An experimental and computational investigation of supersonic combustion flows is in progress. The principal objective of the research is to gain a more fundamental understanding of mixing and chemical reaction in supersonic flows. The research effort comprises three inter-related elements: (1) an experimental study of mixing and combustion in a supersonic plane mixing layer; (2) development of laser-induced fluorescence techniques for time-resolved two-dimensional imaging of species concentration, temperature, velocity and pressure; and, (3) numerical simulations of compressible reacting flows.

During the past year, the design of the supersonic plane mixing layer was completed and the high-pressure gas storage system was installed. The pulsed lasers and camera systems, to be used for two-dimensional flow field imaging, were installed and initial performance evaluations are in progress. Work continued on the development of a detailed spectroscopic model for O_2, a primary species to be measured in our research. Such a model is needed for evaluating potential diagnostic schemes and for interpreting laboratory imaging measurements. Initial imaging experiments on an underexpanded supersonic air jet were conducted, and results confirm that planar laser-induced fluorescence is a viable supersonic flow diagnostic. Initial numerical simulations of compressible turbulence were carried out. This work has focussed on development of appropriate numerical methods for performing full-turbulence simulations of high-speed compressible flows and on the application of these methods to temporally and spatially developing compressible mixing layers. The effort to date has identified several promising numerical methods for compressible flow problems. In addition, a code was developed for compressible mixing layers, and initial simulations using this code show interesting features, such as imbedded shock waves, in high-speed mixing layers.

2.0 INTRODUCTION

An experimental and computational investigation of supersonic combustion flows is in progress. The principal objective of the research is to gain a more fundamental understanding of mixing and chemical reaction in supersonic flows. The research effort comprises three inter-related elements: (1) an experimental study of mixing and combustion in a supersonic plane mixing layer; (2) development of laser-induced fluorescence techniques for time-resolved two-dimensional imaging of species concentration, temperature, velocity and pressure; and, (3) numerical simulations of compressible reacting flows. The specific objectives and the status of the research of each of these program elements is summarized in this report.

3.0 MIXING AND REACTION IN SUPERSONIC FLOW

3.1 Objectives

A primary goal of the research program is to understand the effects of compressibility upon mixing and combustion in a fundamental way. Hence, it is desirable to study as simple a flow as possible so that compressibility effects can be documented in a quantitative way. Three flows are candidates for study from the fundamental point of view: (1) the turbulent mixing layer; (2) the jet in coflow; and, (3) the jet in crossflow. These problems represent increasing fluid-mechanical complexity. For example, the coflowing jet evolves from near-field to far-field behavior, while the transverse jet includes the effects of curved shocks which complicate the fluid mechanical interpretation. The mixing layer on the other hand, while more difficult to construct experimentally, leads to the cleanest interpretation of results, and was, therefore, chosen for this study. The possible use of a mixing layer in the Dual Combustor Ramjet also suggests that it should be studied for its practical application.

An additional benefit of the mixing layer is that the convective Mach number (Bogdanoff, 1983, Papamoschou & Roshko, 1986) has been proposed as a parameter for quantifying the effects of compressibility on the development of the layer. To date, no equivalent parameters have been proposed for the coflowing jet or the transverse jet. There also exists a considerable body of knowledge about mixing layers in the incompressible regime (e.g. Brown & Roshko, 1974, Ho & Huerre, 1984) that can be used for comparison with the compressible case, thus providing clear indications of the effects of compressibility. The mixing layer also lends itself to laser-based imaging techniques. Finally, the two-dimensional turbulent mixing layer is well-suited to attack by numerical computations.

3.2 Experimental Conditions

The primary goals in designing the flow facility were attainment of significant convective Mach numbers and attainment of fast combustion. Consequently, a two-stream, two-dimensional, supersonic, mixing layer facility has been designed and is currently being constructed, see Fig. 1.

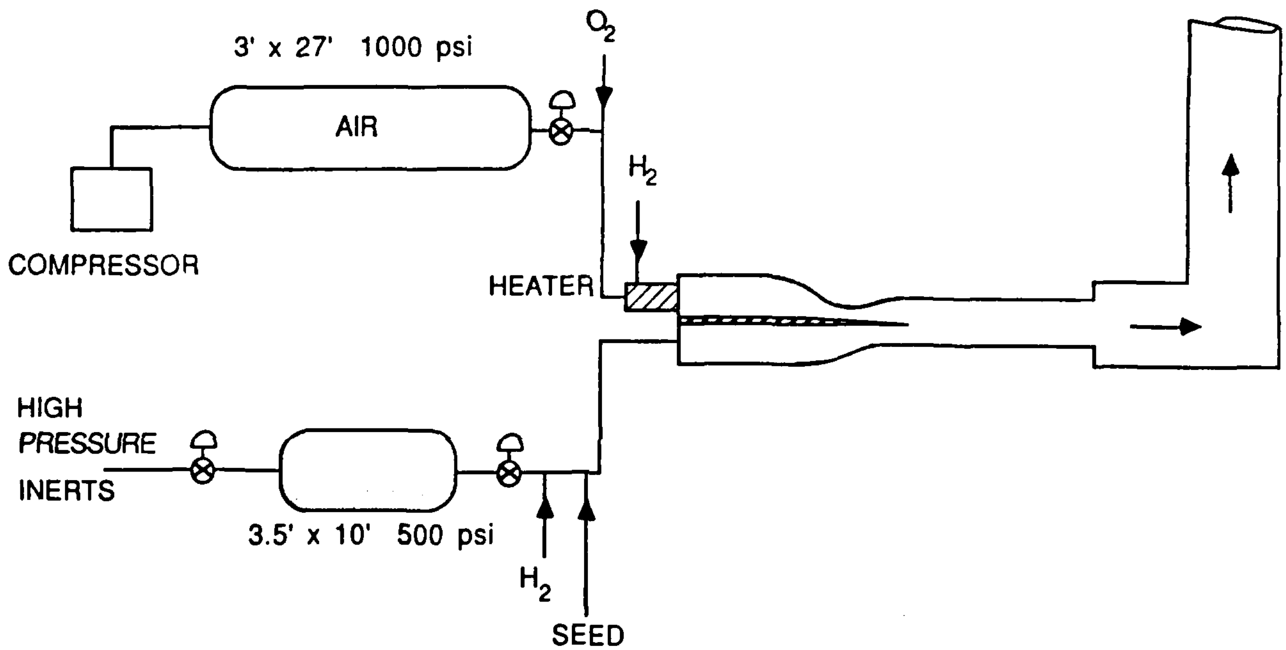


Figure 1. Stanford Supersonic Shear Flow Facility

The high-speed stream consists of a Mach 2 vitiated air stream in a 10 cm x 2.5 cm exit area, with mass flow rates varying from 2.8 kg/s at 300K stagnation temperature to 1.0 kg/s at 2000K. The low-speed stream is nominally Mach 1 in a 10 cm x 3 cm exit area with a mass flow rate of 1.4 kg/s at 300K stagnation temperature. The low-speed stream can be either air or inert gas for the non-reacting mixing experiments or a mixture of inert gas and hydrogen for reacting flow experiments. The test section operates nominally at atmospheric pressure and allows for optical access through all four of its sides. The facility has been designed for a maximum possible high-speed Mach number of 2.5.

The high-speed air is supplied from a pressure vessel, while the low-speed stream is drawn from a second pressure vessel. Maximum run time, limited by the stored gas supply, is approximately 100 seconds. The facility has been designed to handle maximum stagnation temperatures of 2200K. Further details about the facility are provided in Section 3.3.

The definition of the convective Mach number is shown in Fig 2. In determining convective Mach number, the observer shifts from the laboratory frame to that of the dominant large-scale structures which are convecting at a speed U_c. Since the static pressure is everywhere uniform, application of the isentropic compression condition along the two streamlines shown leads to the solution for the convective speed U_c, from which the convective Mach number is then defined as

$$M_{c1} = (U_1 - U_c)/a_1 ,$$

with a similar definition for the low-speed convective Mach number. Significant convective Mach numbers can thus be produced by creating significant shear in the mixing layer, usually by use of a large M_1, leading to large U_1. Additional means are by changing γ_1 or by increasing the stagnation temperature T_{01} at a given M_1.

Figure 3 shows a range of achievable convective Mach numbers for the case of $M_2 = 1.0$, $T_{02} = 300K$, nitrogen, $M_1 = 2.0$, $T_{01} = 300 - 2000K$, vitiated air. A significant range of convective Mach numbers may be obtained simply by changing the high-speed stagnation temperature. The density ratio changes significantly with changes in stagnation temperature, but this is not considered an important issue, since comparisons are usually made with incompressible flows for which the density and speed ratios are the same. Based upon this table, we envision that a significant number of non-reacting experiments will be performed at a high-speed stagnation temperature of 1000K, yielding a convective Mach number of 0.8. Previously measured growth rates (Papamoschou 1986), indicate that $M_c = 0.8$ is the lowest value for which full compressibility effects are felt.

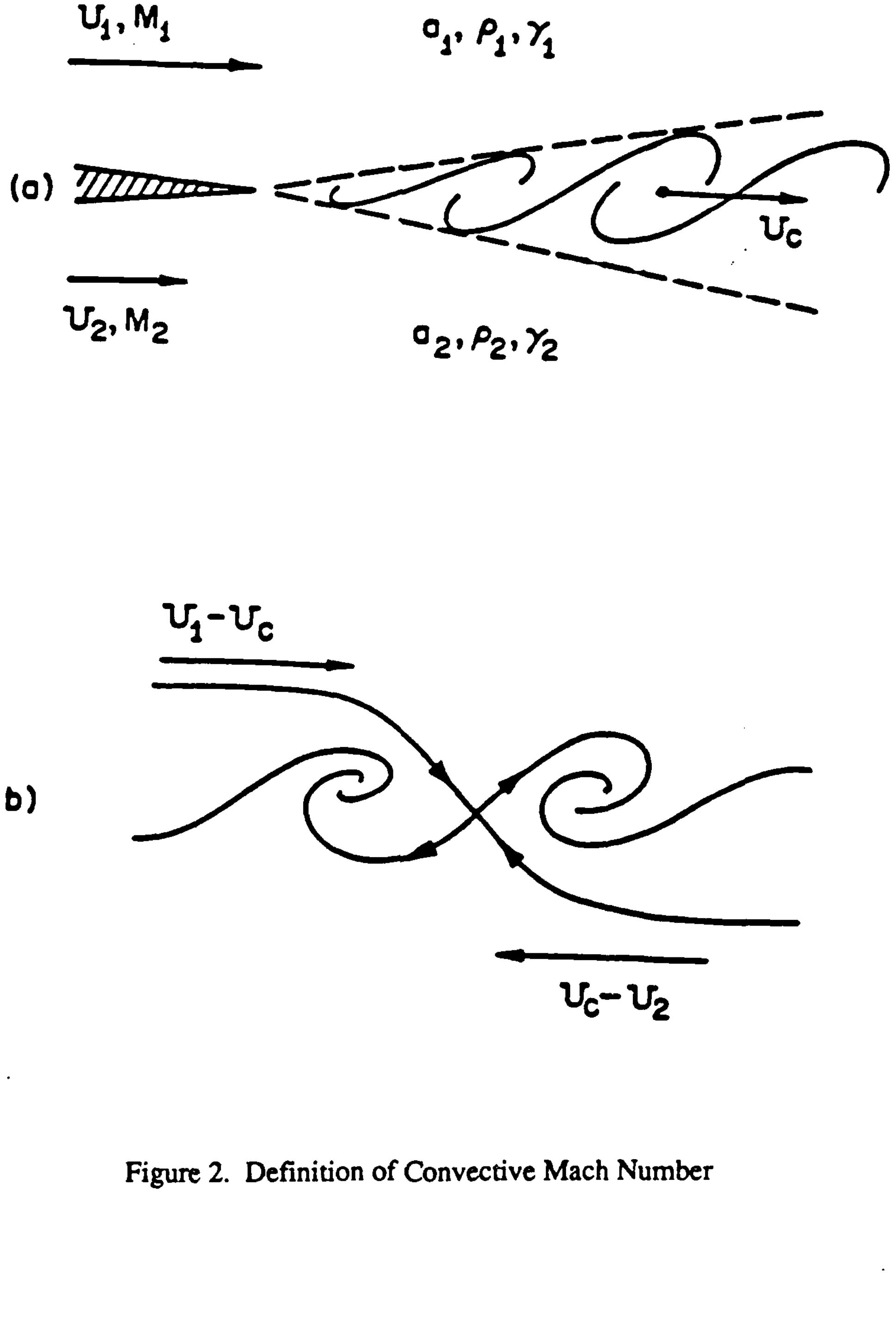


Figure 2. Definition of Convective Mach Number

$M_1 = 2.0$, $M_2 = 1.0$, $T_{02} = 300$ K, $T_2 = 250$ K, $U_2 = 322$ m/sec, $\rho_2 = 1.3$ kg/m^3, $\gamma_2 = 1.4$

$\dot{M}_1$ (kg/sec)	T_{01} (K)	T_1 (K)	γ_1 (stagnation)	U_1 (m/sec)	ρ_1 (kg/m^3)	M_{c_1}	δ / x	Re_1/cm ($\times 10^{-5}$)
2.6	300	167	1.40	517	2.0	.34	.064	3.4
1.8	600	349	1.36	737	.98	.60	.090	2.1
1.5	900	542	1.33	918	.63	.77	.045	1.4
1.2	1200	740	1.31	1080	.45	.89	.054	1.1
1.1	1500	938	1.30	1227	.35	.98	.061	.86
.94	1800	1154	1.28	1375	.27	1.0	.069	.71
.84	2100	1381	1.26	1527	.22	1.1	.077	.60

Figure 3. Expected Run Conditions

For the reacting flow experiments, hydrogen, up to 20% by volume will be added to the low-speed stream. The high-speed stream, consisting of vitiated air, will be run at a stagnation temperature of about 2000K, in order to achieve ignition in the test section. The high-speed Mach number will be lowered, possibly to as low as 1.6, in order to maintain a high static temperature in the test section, with a still significant convective Mach number of about 0.8. Currently, efforts are underway to model the flow and to attempt to predict the expected ignition times and Damköhler numbers.

3.3 Supersonic Flow Facility

This section contains a brief description of each of the main components of the supersonic flow facility.

A gas delivery system supplies and meters four main gas flows: air, nitrogen, hydrogen and oxygen. In addition, smaller flow rates of appropriate seed molecules (e.g. nitric oxide) or ignition enhancers will also be used.

The high-speed side air is supplied by a pressure vessel 180 cubic feet in volume rated at 1000 psi. This system will be charged, usually overnight, by an air compressor system. The low-speed flow may be pure air, pure nitrogen, a mixture of nitrogen and hydrogen, or possibly an alternate inert gas such as argon. Either air, nitrogen or the inert gas will be drawn from a second pressure vessel, 80 cubic feet in volume rated at 500 psi. The hydrogen and oxygen flows will each be supplied by 10 to 20 standard 2200 psi gas cylinders connected to a manifold.

From their respective sources, the gases are accurately metered before entering the facility. All metering is accomplished using critical flow venturis. Mass flow rates will be controlled by setting the stagnation pressures at the venturis using a personal computer and five controller-globe valve combinations (one for each gas line). The computer is also used to control the entire start-up, shut-down and emergency sequence of the facility.

In order to achieve high convective Mach numbers in the non-burning mixing studies, it is necessary to heat the high-speed stream by several hundred degrees K. Further increasing of the high-speed stagnation temperature, to about 2000°K, would be required for the auto-ignition of hydrogen and air within the mixing layer during burning studies. To achieve the required wide range of high-speed stream stagnation temperatures needed, a Marquardt Co. SUE (SUdden Expansion) burner has been chosen. This device produces a vitiated air stream by burning hydrogen in air, together with make-up oxygen.

The setting chambers, supersonic nozzles, test section and supersonic diffuser have been designed similar to that of Papamoschou (1986). The essential difference is that the high-speed stream is designed for stagnation temperatures in excess of 2000K. Stainless steel, copper and ceramics, together with appropriate water cooling have been used extensively in the facility. The high-speed Mach number is designed to be 2, while the low-speed is sonic. The test section is 5.5 cm high, 10 cm wide and 50 cm long. The height is set by the sum of the 2.5 cm (high-speed) and 3 cm (low-speed) nozzle exit heights. The asymmetry of the test section was introduced since the existing evidence shows that the layer penetrates further into the low-speed side of the flow, necessitating greater distance to reduce wall interactions. At the station of interest, about 35 cm downstream, an estimate of the mixing layer growth shows the layer width-to-thickness ratio to be about 6, thus ensuring good two-dimensional behavior. Furthermore, at this location, the layer occupies less than half the height of the test section.

Additional important features of the test section are the adjustable upper and lower walls enabling changes in the streamwise pressure gradient and optical access from all four sides required for the planned laser diagnostics.

On exiting the test section, the exhaust gas enters a supersonic diffuser consisting of a straight pipe seven hydraulic diameters in length, before it is dumped into a 20 inch diameter exhaust duct. The flow is cooled by use of high pressure, finely atomized water sprays before it exits through the exhaust stack.

3.4 Status of the Research

The gas storage system has been put in place and tested. The facility design is complete and currently under bid from several fabricators. The gas heater is expected in December 1987.

3.5 Future Work

In the next reporting period, we expect to complete full assembly of the flow facility, debug it and proceed through several values of stagnation temperature available from the flow heater. Preliminary measurements of the growth of the layer from incompressible through compressible conditions will be completed. Intrusive measurements using hot wire and thermocouple probes will be completed. This documentation of the flow will provide the flow qualification before non-intrusive measurements are begun.

4.0 SUPERSONIC FLOW DIAGNOSTICS

4.1 Objectives

This aspect of the research is aimed at developing flowfield imaging diagnostics based on Planar Laser-Induced Fluorescence (PLIF). Flow parameters of interest include species concentrations (or mole fraction), temperature, velocity and pressure. Particular emphasis is placed on imaging molecular oxygen, since this species is naturally present in nearly all supersonic flows of practical interest.

4.2 Status of the Research

Work during the first reporting period has been in five areas: (1) small-scale flow facility development; (2) laser testing and development; (3) uv imaging camera development; (4) oxygen (O_2) fluorescence spectroscopy calculations; and (5) initial fluorescence imaging experiments in oxygen.

4.2.1 Small-Scale Flow Facility Development

In order to provide a realistic test environment for developing O_2 imaging schemes in supersonic flows, a small-scale supersonic flow facility was designed and assembled. The system, now in use, includes a 400 cfm vacuum pump and allows continuous operation at pressures down to a few Torr. The gas, usually air, may be heated electrically to about 1000 K to provide a range of stagnation temperatures. The test section provides optical access to view the region immediately downstream of interchangeable nozzles. This small system is simple and economical to operate, and will allow convenient evaluation of candidate imaging concepts. Eventually, the successful schemes will be utilized in the large-scale supersonic mixing layer facility.

4.2.2 Laser Testing and Development

The utility of a broadband argon fluoride excimer laser (1 nm bandwidth at 193 nm) for PLIF imaging of heated, atmospheric-pressure, non-reacting air has been shown (Lee, Paul and Hanson, 1986 and 1987). This large spectral width leads to excitation of a large number of O_2 transitions which, when taken together, exhibit a strong temperature dependence useful for imaging temperature. For reacting supersonic flow, however, where pressure, temperature and O_2 mole fraction can all vary, a tunable, narrow-linewidth laser source is preferred so that individual rovibronic transitions may be excited. This single-line excitation strategy enables some decoupling of the fluorescence signal dependence on multiple flow parameters, and the use of single-line excitation at multiple wavelengths (two or three) appears to offer the best prospect for simultaneously determining both temperature and O_2 mole fraction in reacting compressible flows. Accordingly, a tunable, narrow-linewidth excimer laser (Lambda-Physik, 160T MSC) was acquired and installed, and experiments to characterize its performance with regard to linewidth, energy/pulse, stability and line-locking ratio have been conducted.

The results of these initial tests were disappointing in that the laser worked well at KrF (248 nm) and XeC1 (308 nm) wavelengths, but the performance at the desired ArF wavelength, 193 nm, was much poorer. The laser has been rebuilt and purge covers were installed on the laser to reduce interference absorption by O_2 in the air paths of the laser cavity. Tests are resuming on system performance, and we are hopeful that these changes will be sufficient to recover the expected laser performance.

A closely related effort, still in progress, is assembly of a Raman shifter which will function at vacuum ultraviolet wavelengths (anti-Stokes shifts of ArF). Such a device should allow simultaneous generation of laser light in two discrete regions (e.g. 193 and 179 nm), as may be needed for multi-wavelength excitation for simultaneous determination of temperature and O_2 concentration.

4.2.3 UV Imaging Camera Development

A critical feature of O_2 imaging is the fact that the fluorescence is largely in the ultraviolet region of the spectrum. This leads to a requirement that the photocathode of the camera intensifier be sensitive at these wavelengths. The low light levels expected lead to a further requirement on the size of the camera pixels, namely that they be large enough to capture enough photons to provide the needed signal-to-noise ratio. These combined requirements have led to a design for an advanced, sensitive uv imaging system based on a Reticon photodiode array (128 x 128 pixels) with an attached fiber-optic bundle. A single microchannel plate intensifier (S-20 photocathode) is employed with the camera stub butted directly to the phosphor output of the intensifier. This camera system is controlled by a Microvax I computer. The entire system has been assembled and is now operational.

4.2.4 Oxygen Fluorescence Spectroscopy Calculations

Work has continued on development of a detailed and complete spectroscopic model for O_2 which can be used for quantitative calculations of absorption and fluorescence over a broad range of temperature and pressure. Such a model is needed for evaluating potential PLIF diagnostic schemes and for interpreting laboratory imaging measurements. Further, the development and use of the model will reveal those fundamental parameters, such as electronic quench rates, which may require measurement to enable quantitative use of the O_2 diagnostic scheme selected. The model is now nearly complete, after about three man years of effort, and is currently being utilized to explore candidate imaging schemes for simultaneous determination of temperature, O_2 concentration and velocity.

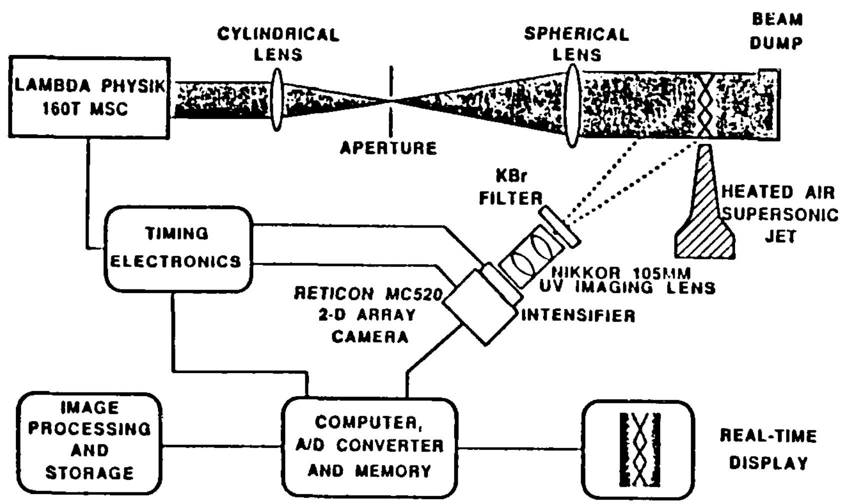
One publication has resulted already from this modeling work (Lee and Hanson, 1986), and others are expected as promising schemes for imaging multiple quantities emerge.

4.2.5 Fluorescence Imaging Experiments

Initial imaging experiments in supersonic air flows were carried out using the small-scale flow facility described above. Unfortunately, the work was done before the new camera system (described above) was available. As a result it was necessary to use a noisy camera with a degraded intensifier. Nonetheless, the data provide confidence in the general approach being taken and are useful input for planning future experiments.

The laser used was the new tunable ArF laser, prior to its modification, tuned to excite a single transition of O_2 in an underexpanded jet of heated air. Sample imaging results are shown in Fig. 4; to our knowledge, these are the first two-dimensional O_2 images obtained in supersonic flow in any laboratory.

The fluorescence signal which results from exciting a single O_2 transition is the product of a temperature dependent function (the line-center absorption coefficient) and the partial pressure of O_2. The temperature dependence of the signal for the transition chosen is illustrated in Fig. 5. Since, in the expanding flow, temperature and pressure increase (or decrease) together, bright regions of the image in Figure 4 can be identified as regions of relatively high temperature (regions which have been recompressed by weak shock waves) while the low signal regions are those of low temperature (and pressure). Use of such image data to separate the two variables (temperature and pressure) will require excitation at two separate wavelengths. Although the current data



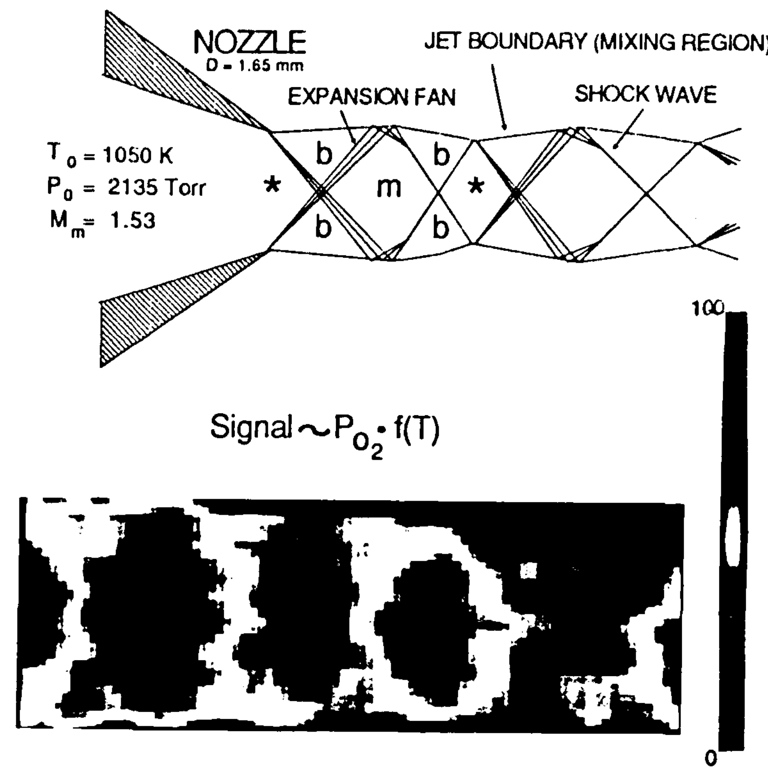


Figure 4. Supersonic Flowfield Imaging of Oxygen (O_2).

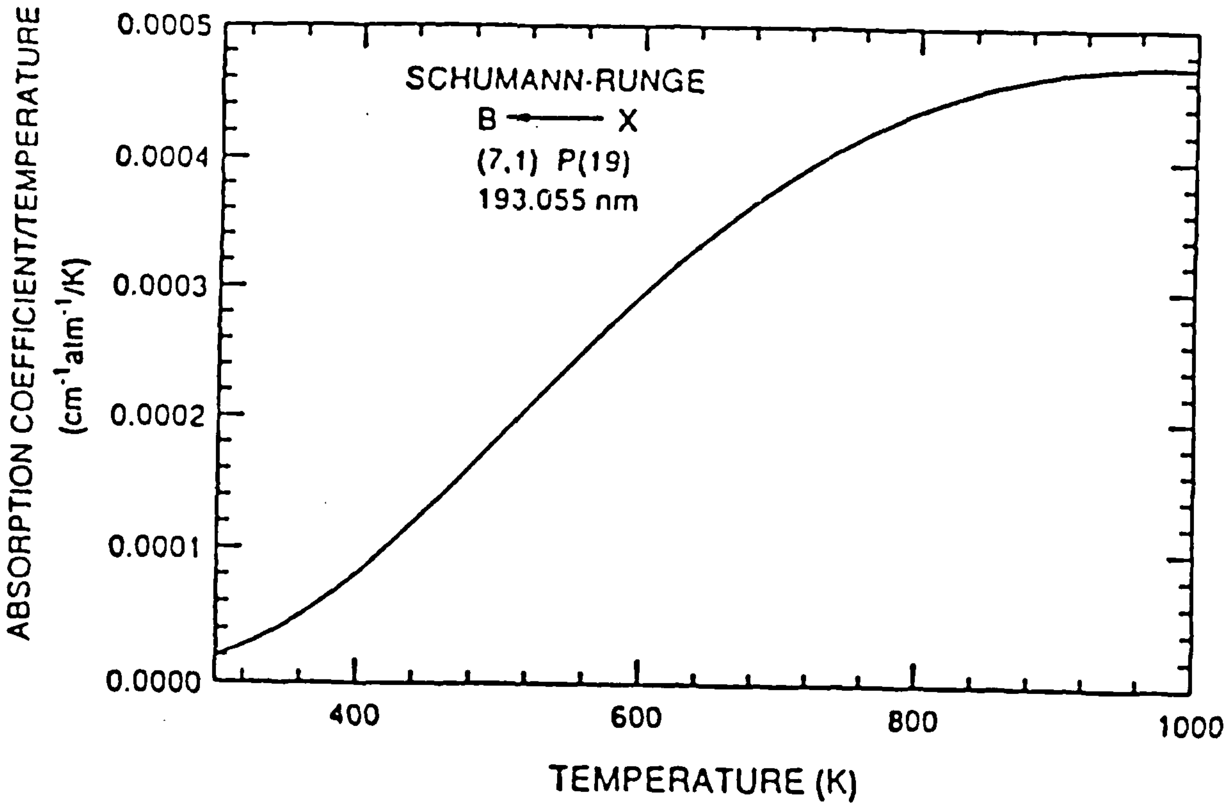


Figure 5. Absorption coefficient for O_2 at 193.055 nm.

are of low quality relative to what will be achieved with the new camera system, they serve to confirm the PLIF concept as a viable supersonic flow diagnostic.

4.3 Future Work

During the next year work will continue in a number of areas.

An upgrade of the small-scale supersonic flow facility, which will allow testing at higher stagnation enthalpies and flow speeds, will be considered. This upgrade likely will involve use of a high power electric arc which operates at a few atmospheres pressure. In addition, a shock tunnel which would provide a few milliseconds of test time at hypersonic flow conditions is being designed. Such a test facility would allow critical demonstrations of the planar laser-induced fluorescence technique at extreme flow conditions relevant to hypersonic flight research issues. The successful demonstration of imaging diagnostics in such flows would be of significant value in high-speed aerodynamics and propulsion research in other laboratories in this country and elsewhere.

Work will continue on the development of tunable narrow-line excitation schemes for simultaneous imaging of O_2 mole fraction and temperature in compressible flows. Additional tests will be conducted with the modified ArF excimer laser to characterize its performance. Work also will continue on the assembly and characterization of the Raman shifter for generation of laser light at two wavelengths needed for these imaging experiments.

The O_2 spectroscopic model will be completed during the next reporting period, and the model will be employed to explore various schemes for simultaneous imaging of temperature, O_2 concentration and flow velocity.

During the next year, additional O_2 fluorescence imaging experiments will be conducted using the new uv camera system. Work will proceed on development of techniques for excitation at two separate narrow-linewidth wavelengths with broadband detection of both wavelengths. Schemes for velocity imaging, based on the Doppler shift of absorption lines, will be evaluated.

5.0 NUMERICAL SIMULATIONS OF COMPRESSIBLE TURBULENCE

The numerical simulation and modelling component of this research project is broken into two parts. The first part will consider basic turbulent flows which can be examined in detail in order to help develop turbulence models for use in complex compressible flows of interest. The second area of study is the simulation of temporally and spatially developing compressible mixing layers. The progress made on these two projects and plans for future work are described in the following sections.

5.1 Basic Turbulent Flows

5.1.1 Objective

The objective of this portion of the project is to simulate basic turbulent flows in order to aid the development of turbulence models. The basic turbulent flow fields considered will be idealized in that they will be homogeneous. The simulation of homogeneous turbulence has been useful in the development of turbulence models for incompressible flows. A similar approach will be followed for compressible flows.

We have decided to concentrate on homogeneous sheared turbulence since it is a very important canonical flow for engineering applications. Compressible homogeneous shear flow has been studied by Feiereisen et al. (1981). In the current study, his results will be extended by making runs with higher fluctuating Mach numbers, allowing a greater effect of compressibility. Also, by carrying equations for a marker in the fluid, it will be possible to investigate the effects of compressibility on mixing.

5.1.2 Status of the Research

To date, the research has focussed on the search for appropriate numerical methods for performing full-turbulence simulations (FTS) of high-speed compressible flows. Spectral methods have been used in incompressible flows and are attractive because of their high spatial resolution, but they may not be appropriate for the current applications because they suffer from Gibbs' phenomena in the presence of discontinuities. In a viscous flow there are no true discontinuities; however, shock waves and contact surfaces can cause spurious oscillations if the gradients in the flow variables are too steep.

In order to test the usefulness of spectral methods a one-dimensional code was written to solve shock tube problems. The results show that if the Reynolds number of the flow is low enough the shock waves will be well-resolved and the spectral method will be useful. Recently Passot and Pouquet (1987) used a spectral method to simulate the decay of two-dimensional isotropic turbulence with high fluctuating Mach numbers. Their results are encouraging for the usefulness of spectral methods in simulating high-speed compressible turbulence. The amount of resolution needed depends on the results desired. If one wants qualitative information about the structure of the flow, only a few grid points are needed to resolve a shock. If one is interested in calculating the values of quantities used in modelling, for example the dissipation, then more resolution is needed.

The task of simulating homogeneous flows has been broken into two steps. The first is the simulation of decaying isotropic turbulence. The second is the simulation of homogeneous sheared turbulence. Currently these problems have been formulated and the codes for performing the simulations are being constructed.

5.1.3 Future Work

The first goal for this portion of the research project over the next year is completion of the isotropic turbulence code. The results of these simulations will be compared to simulations by other investigators (Passot and Pouquet 1987, Erlebacher et al. 1987, Dang and Morchoisne 1987). The shear flow simulations will then be performed using initial conditions generated by the isotropic code. Initial results will be compared to those of Feiereisen et al. (1981). Further simulations will be run to create data bases of compressible turbulent flow fields.

Having full simulation data available will allow the evaluation of terms necessary for turbulence modelling which would not be available otherwise. In addition, it will be possible to examine the structure of the turbulent flow field to better understand the underlying physics.

5.2 Compressible Mixing Layers

5.2.1 Objective

The objective of this portion of the project is to develop a capability for full simulation of both temporally and spatially developing compressible mixing layers. The time-developing simulations will be used to study the fundamental physics of the compressible mixing layer, including shock-wave structure, vortex pairing and three-dimensional effects. The spatially-developing simulations will be designed to more closely match the experimental situation and these computations will be used to investigate in detail the convective Mach number concept and to study entrainment and mixing in the compressible mixing layer.

5.2.2 Status of the Research

Work during the past year has been in two areas. First, using an existing low speed mixing layer code inflow boundary conditions were developed which allow numerical simulations of free shear layers to more closely match experiments. Second, various numerical methods for simulation of compressible mixing layers were investigated and these have been implemented in a new two-dimensional code for solution of both time-developing and space-developing shear layers.

The full simulation of spatially-developing free shear layers is complicated by the requirement of specifying inflow and outflow boundary conditions. We have experimented with various inflow boundary conditions using the low-speed mixing layer code developed by Lowery and Reynolds (1986), with a view to developing new boundary conditions which we will be able to use in compressible simulations. Full simulations of the Navier-Stokes equations operate at low Reynolds numbers in order to capture all the relevant scales of motion. For the mixing layer this means that forcing has to be applied in order to prevent relaminarization and, so, the simulations of Lowery were limited to forced mixing layers. In recent work, it was found that a random-walk applied to the phase of the forcing eigenfunctions was an effective method of randomizing a forced simulation in order to achieve simulation of a 'natural' mixing layer. In addition, it was found that the large initial asymmetry of entrainment which has been observed experimentally can be captured in the simulations if the wake from the splitter plate is included in the initial velocity profile. Details of these simulations are fully documented in Sandham and Reynolds (1987).

Since we expect to find shock waves in high Mach number simulations it was decided to investigate some of the 'shock-capturing' numerical methods which have been developed over the last 10 years. These modern methods attempt to capture shock waves without spurious oscillations (Gibbs' phenomena) and also with a minimum of 'artificial viscosity, the use of which characterized earlier attempts to capture shock waves. There are a multitude of these numerical methods available, for example FCT (Flux Corrected Transport), TVD (Total Variation Diminishing) and ENO (Essentially Non-Oscillatory). We have chosen to test schemes of the TVD type which have advantages over FCT of ease of implementation and probably better overall accuracy. The relative merits of ENO schemes are not clear at the moment since they are a very recent development and have only been tested for one-dimensional gasdynamic problems.

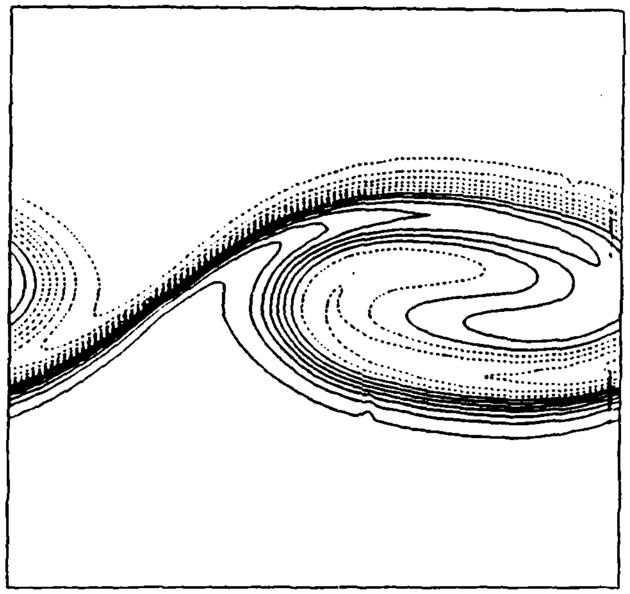
A two-dimensional code has been developed which solves the full compressible Navier-Stokes equations on an orthogonal grid and implements the 7 varieties of TVD schemes described in Yee (1987), as well as the conventional MacCormack method for comparison purposes. The TVD part of the code was checked by running a shock reflection problem for which an exact solution exists. In addition to the Navier-Stokes equations, the code also solves a passive scalar equation, which in effect means that two species are computed. Contour plots of mixture fraction reveal very clearly the structure of the layer, and the species information will allow a detailed study of entrainment and mixing in compressible mixing layers. The code can be used for both temporally and spatially-developing mixing layers.

Figure 6 shows the results for mass fraction and density obtained from a time developing simulation in which a single vortex was excited. A 100×100 grid was used, with a Reynolds number of 200 and a Mach number of 0.8 (upper stream moving to the right at M=0.8 and the lower stream to the left at M=0.8). This is the first Mach number at which the formation of shock waves embedded in the vortices is observed. The initial density of the two free streams was 1 and contours of densities less than 1 are shown with dashed lines in the plot. Flow above and below the vortex is accelerated to supersonic speeds (up to approximately M=1.2) and then is compressed through a shock wave which lies slightly behind the vortex. The density is lowered in the center of the vortex and is a maximum in the braid region of the mixing layer. The mass fraction contour plot shows how fluid is rolled into the vortex - fluid which originated on the upper side is shown with solid contours and fluid from the lower side with dashed contours. The transport of unmixed fluid from one side of the layer into the other by the large-scale structure is the same as that observed in the low-speed mixing layer.

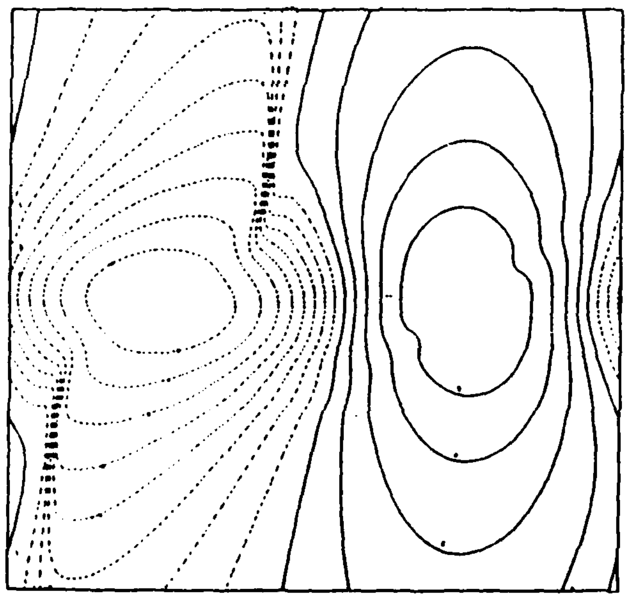
Figure 7 shows some early results from a spatially-developing simulation where the upper stream is at Mach 2 and the lower stream is at Mach 1. The velocity ratio is 0.6, with a Reynolds number of 200 based on initial vorticity thickness and a convective Mach number of 0.35. A grid of 600×150 was used and forcing was applied at a fundamental frequency and two subharmonics. At these lower convective Mach numbers no shock waves are seen embedded in the vortices and the mixing layer growth rate is comparable with that for an incompressible mixing layer at the same velocity and density ratio. For this simulation the MacCormack method was used for the Navier-Stokes equations and a TVD scheme was used for the passive scalar.

5.2.3 Future Work

Work planned for the coming year includes a continuation of the study of two-dimensional mixing layers using MacCormack and TVD methods as well as investigating the possible use of spectral methods for a three-dimensional simulation of the time-developing compressible mixing layer. We also plan to investigate the compressible linear stability problem and use the eigenfunctions from these studies as forcing functions in our full simulations.

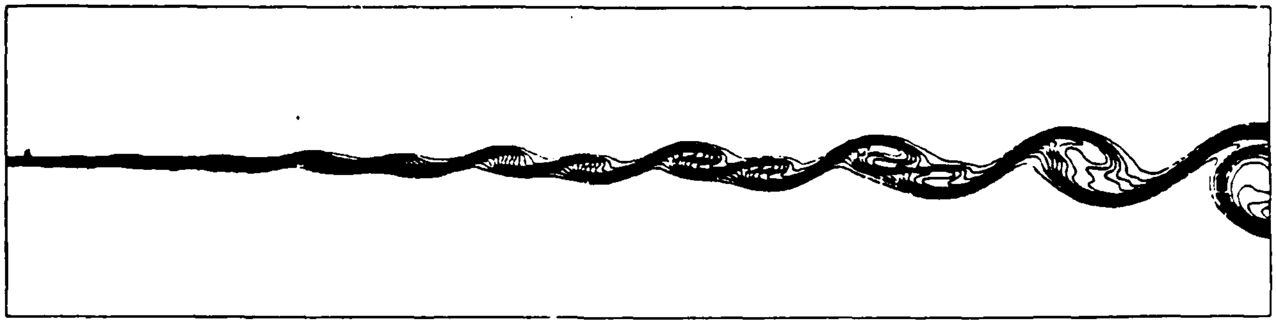


MIXTURE FRACTION CONTOURS

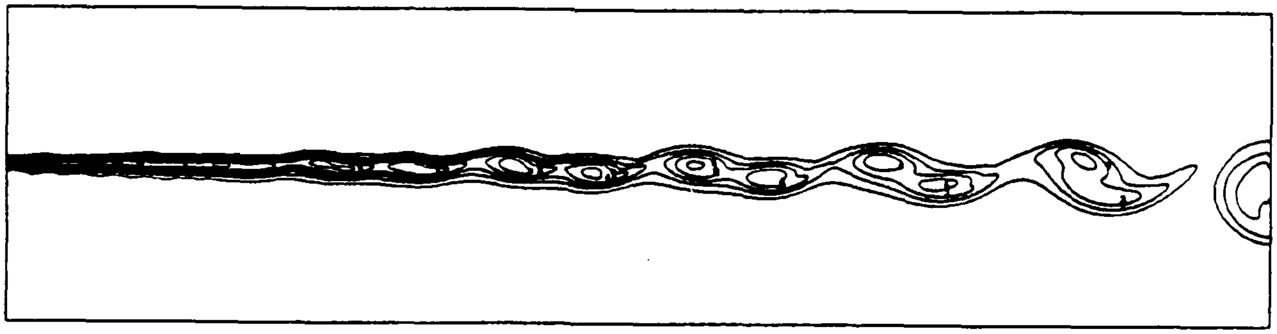


DENSITY CONTOURS

Figure 6. Time-developing mixing layer simulation. Convective Mach number 0.8, Reynolds number 200. Contour plots of mixture fraction and density.



MIXTURE FRACTION CONTOURS



VORTICITY CONTOURS

Figure 7. Spatially-developing mixing layer. Upper stream Mach 2, lower stream Mach 1, convective Mach number 0.35, Reynolds number 200. Contour plots of mixture fraction and vorticity.

6.0 PUBLICATIONS AND PRESENTATIONS

During this reporting period the following papers were written and presented:

1. L. M. Cohen, M. P. Lee, P. H. Paul and R. K. Hanson, "Two-Dimensional Imaging Measurements in Supersonic Flows Using Laser-Induced Fluorescence of Oxygen," AIAA reprint 87-1527, AIAA 22nd Thermophysics Conference, June 1987.

2. N. D. Sandham and W. C. Reynolds, "Some Inlet-Plane Effects on the Numerically Simulated Spatially-Developing Two-Dimensional Mixing Layer," Turbulent Shear Flows 6, Toulouse, France, 1987.

7.0 PERSONNEL

Craig T. Bowman	Professor, Mechanical Engineering
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8.0 PROFESSIONAL INTERACTIONS

During the past year, we have had numerous interactions with individuals at government, industrial and university laboratories involved with supersonic combustion, laser diagnostics and computational fluid dynamics.

In the area of supersonic combustion, we have established a working relationship with Cal Tech, the University of Illinois, NASA/Ames and NASA Langley Research Centers, and the Applied Physics Laboratory. We have had numerous visitors not only from these organizations, but also from companies involved in the National Aerospace Plane (NASP) project, including McDonnell-Douglas and General Electric.

Our research on oxygen flowfield diagnostics has generated considerable interest in the aerodynamics and propulsion communities, particularly owing to the potential utility of the methods for research related to the NASP. The level of interest shown suggests that this research project has potential for significant impact on the national research effort for NASP.

The computations are being carried out in collaboration with the NASA/Ames Research Center, which is providing computer time on Ames supercomputers. Ames' experts in numerical analysis for turbulence and compressible flows have provided important consultation in the development of the programs. This work has been integrated into the supersonic simulation effort of the new Stanford/Ames Center for Turbulence Research, which has identified the simulation of compressible turbulence as a key thrust area.

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